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# TECHNICAL AND ECONOMICAL BENEFITS OF AVIATION CBM IN MAINTENANCE, REPAIR & OVERHAUL (MRO) - REVIEW

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**ABSTRACT**

Maintenance along with its technical and management activities during repair periods has impact on a product or an asset's economic factors. Maintenance plans have been divided into several categories, including condition based maintenance - CBM, preventative maintenance, and breakdown maintenance. While preventative maintenance frequently inspects a product at predetermined intervals to avoid abnormalities, breakdown maintenance is performed once certain issues, such as product breakdowns, are discovered. All these require higher cost values and passive in avoiding defects ahead. The contents of this paper are concerning CBM in technical systems. It has also been shown that the traditional maintenance techniques, corrective and preventive, are very costly. With CBM one utilizes predictive maintenance, i.e. perform maintenance based upon need. One assesses the condition of the assets and makes judgments whether or not maintenance should be performed. This indicates that the maintenance intervals will be decided dynamically. Vibrations, temperature, oil, acoustic analysis etc. are some of the basic parameters that will reveal the condition. There are also just a few areas in the industry where CBM (or possibly even just condition monitoring) have gained acceptance.

**Keywords:** Maintenance, Aircrafts, Gas turbine engines, MRO, RCM, CBM

## I. INTRODUCTION

CBM is a maintenance strategy that uses collected product data from external tests using embedded sensors [1]. Data can be acquired from measurements made by portable equipment to forecast live risk of product failures [2]. The CBM is concerned with failure prediction and deterioration monitoring in addition to component diagnostics and fault detection. Recently developed technologies like various sensors such as Radio Frequency Identification - RFID, Micro-Electro-Mechanical System - MEMS, wireless Tele-communication, Product Embedded Information Devices - PEID, and Supervisory Control & Data Acquisition - SCADA are supporting the effectiveness of maintenance activities [3].

In the predictive maintenance, the asset's state is assessed through analysis [4]. CBM is a best option which helps to pinpoint the exact parts of the object that are deteriorating and provide a diagnosis. The CBM process is widely used to maintain operations in a variety of industries. It is a maintenance approach that is predicated on evaluating an asset's state to determine whether it may fail at some point in the future [5]. Its foundation lies on tracking the equipment's underlying deteriorating process and as a result costs associated with technical and operational maintenance may be reduced [6].

## II. LITERATURE REVIEW

### 2.1 Maintenance Concepts and Classifications

The importance of maintenance to a company's profitability and competitiveness has grown in recent years. As a result, there is now greater emphasis on the necessity of choosing the most economical maintenance for a particular part or piece of equipment under certain conditions [7-9].

#### 2.1.1 Corrective Maintenance

Corrective maintenance (CM) is described as maintenance performed after a fault has been identified. The repair can wait as long as the breakdown does not affect the overall function [10]. The strategy with the highest operating cost, lowest investment and the lowest equipment availability is corrective maintenance [11]. The CM is divided into delayed and immediate maintenances. When a fault is identified, CM does not immediately do it; instead, it is postponed in accordance with established maintenance guidelines. When maintenance deferred, component, or system performance quickly declines [12,13].

However, immediate maintenance refers to CM that is performed as soon as a fault is identified [10].

### 2.1.2 Reliability Centered Maintenance (RCM)

RCM is a technical maintenance strategy that, like CBM, aims to determine the best methodology depending on the maintenance needs of each asset. Some RCM maintenance strategies that are used for different systems are; Reactive maintenance; Preventive maintenance; Predictive Maintenance; Proactive Maintenance; Run-to-Failure (RTF) and CBM [14,15].

Reactive maintenance is applied when an asset already breaks down. Predictive maintenance predicts chances of failure of system or equipment where as a Proactive Maintenance is that generally works on root causes of failure and simply avoids chances of failure occurrence. Run-to-Failure (RTF) is the practice of using equipment until it breaks down, at which point it is replaced or repaired. CBM approach focuses on tracking particular variables that have a direct effect on how well equipment performs [4,15-16].

## 2.2 Condition Based Maintenance Concepts

### 2.2.1 CBM Development

Rio Grande Railway Company first presented the idea of CBM in the late 1940s, when it was known as predictive maintenance. A study conducted as part of Boeing 747 preventative maintenance program development in the 1960s made clear the necessity for CBM aimed to identify the aircraft component failure characteristics [17].

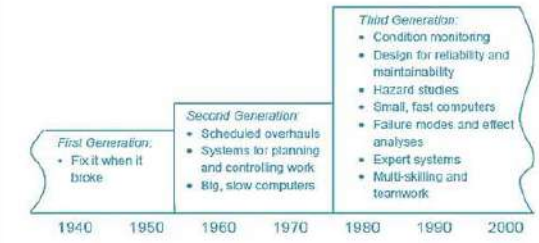


*Figure -1: Maintenance stage of development in three generations.*

### 2.2.2 CBM Implementation Methods

The CBM programs should be designed and implemented through well-defined goals and a cost effective investment strategy [18]. Mostly the implementation of a CBM approach implies that an entire company needs to be involved and old routines need to be changed into new [19]. This is because many techniques are expensive, and it would not be cost effective [15,20]. The implementation of systems requires a combination of feature extraction, sensor data fusion, prediction algorithms, and classification [21]. A four-point implementation guideline is available to help organizations introduce condition-based maintenance more smoothly [22]. Figure 3 shows the four phases implementation methods. The process starts with a feasibility test to investigate whether a CBM approach is applicable or not. If ok, the process continues with an analysis phase, which is supposed to answer questions as shown in Figure 3. Following the answers to these questions, the process continues with an implementation of the technical solutions in an organizational setting by continuously assessing the continuous improvements [23].

*Figure -2: The four phases of implementation method*

***i.Decision support***

Three steps are included in the decision-making process: listing all alternative strategies, evaluating all consequences followed up, and assessing the results. When making decisions, people need to interact with each other, and it's not necessary to share the complete strategy with everyone [24]. On one level, decisions made by organizations are separated into two categories: programmed and unprogrammed. It is better to explain how to selec the appropriate on-condition job within the RCM framework [15,25]. When implementing CBM, three decisions must be made: deciding which parameters to monitor, how often to conduct inspections, and what the warning limit should be [26]. A monitoring decision algorithm is used to select proper assets using the proper technique. The algorithm starts with an overall criticality survey, using tools such as: Fault Tree Analysis (FTA), FMECA, and RCM [27].

***ii.CBM Data Availability***

The primary challenges to alignment type of aviation CBM are those related to data quality, quantity, availability and timeliness for use in prognostics, diagnostics, and detection. The CBM application will determine which sensors and technologies are used [28]. The sensors' reliability to be employed in CBM will play a major role in their reliable applications [29]. It is well known that CBM uses computers extensively for data storage, analysis, and gathering. A block diagram that is perfect for a CBM program may be found in the figure below. Both online and offline approaches can be used for CBM defect detection used for diagnosis and prognosis methods. Accurate and timely detection and prediction of problems that develop quickly may be difficult [30].

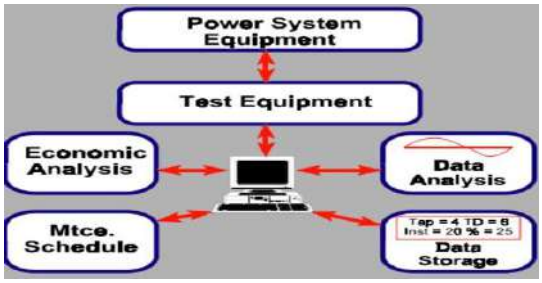


*Figure -3: Block diagram of equipment set for CBM data structure*

There could be discrepancies between the data and meta-data that CBM developers gather. They use and integrate it into CBM solutions. End users may be less likely to embrace CBM solutions if there are inaccurate predictions [31].

## 2.3.CBM Program

End users can confidently minimize time-based maintenance intervals, reduce or eliminate needless inspections, and carry out better planned maintenance thanks to CBM. Installing monitoring equipment, developing decision-making method, and providing staff training are all necessary before implementing the CBM. Furthermore, the CBM technological approaches and technologies are not developed well. It implies that there are certain restrictions on guaranteeing the precision of prognostic and diagnostic information [3,32]. Three essential processes make up a CBM program like data acquisition, processing and final maintenance decision [33,34]. In a CBM program, the diagnostics include fault isolation, identification, and detection. Prognostics studies defect prediction before it happens. Prior event analysis is a prognosis, and posterior event analysis is a diagnostic [35-37].

### *i. Data Acquisition*

A CBM program's initial section deals with data acquisition, or the procedure of gathering and archiving relevant information from engines for CBM uses. Event and CM data are the two categories of data that can be obtained [37]. Data from condition monitoring are incredibly flexible. Numerous sensors, including acoustic emission sensors, ultrasonic sensors, and micro-sensors, have been developed to gather diverse kinds of information [38-40].

### *ii. Data Processing*

Data processing, which consists of two primary procedures: data cleaning and data analysis, makes up the second part of a CBM program [37]. Data cleaning makes sure that clean, error-free data are used for additional analysis and modeling. Numerous factors, including human error, contribute to data errors [41]. Data analysis is the next stage of data processing. The types of data that are collected determine the models, methods, and tools that are utilized for data analysis [33,42-43].

#### *a. Data Cleaning*

The initial stage of data processing is data cleaning. The obtained measurements are now filtered to lessen measurement noise and verified using the proper sensor validation methods. Measuring noise can be substantial and by itself result in an inaccurate assessment of the health of the engine [40,44].

#### *b. Data analysis*

Data analysis is the second stage of data processing. In order to extract useful information for the decision-making part of CBM for diagnostic and/or prognostic purposes, the obtained measurements are further analyzed at this stage [37,44-45].

*Figure -4: Components of CBM approach*

Combining condition monitoring and event data analysis has advantages. By creating a mathematical model that accurately explains the underlying mechanism of a malfunction or failure, this integrated data analysis can be completed [46-47].

### *iii. Decision Making*

Decision making is the third part of a CBM program and it covers two areas such as diagnosis and prognosis. It has attracted interests of researchers for the past few years in CBM practices and its associated theories [26,48]. Prognostics can also be improved with diagnostics with more accurate event data for building better CBM model [47,49].

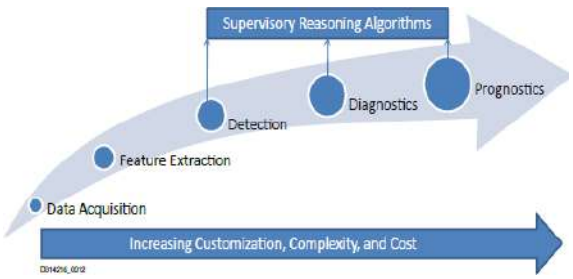


*Figure -5: The Detection, Diagnostics and Prognostics (DD&P) process*

### a. *Diagnosis*

The process of discovering, isolating, and diagnosing an imminent failure condition during which the affected component function in a degraded mode is known as fault diagnostics. One way to define diagnosis is the process of applying logic to determine the state of mechanical equipment's health based on information gathered during operation [50]. The primary goal of diagnosis is to notify engineers soon after the monitored equipment is functioning abnormally [51]. There is an extent bibliography on gas turbine diagnostics, containing a large number of methods that have been proposed by many researchers. Fault detection, isolation and identification can further be defined as shown below [34,52].

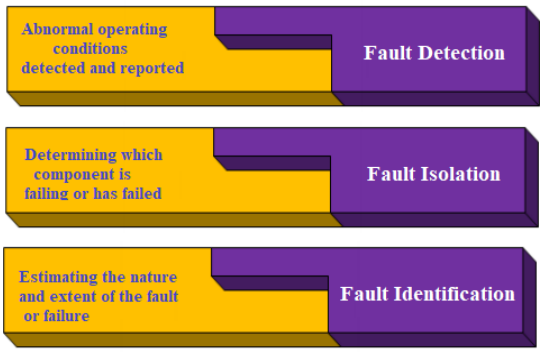
Abnormal operating conditions detected and reported
Fault Detection
Determining which component is failing or has failed
Fault Isolation
Estimating the nature and extent of the fault or failure
Fault Identification

*Figure - 6: Fault diagnosis procedures*

### b. *Artificial Intelligence (AI) approaches*

AI techniques have been increasingly applied to machine diagnosis and have better performance over conventional approaches. Expert Systems and artificial neural networks (ANN) are two well-liked popular AI methods for machine diagnosis. Neural–fuzzy systems, fuzzy logic systems, fuzzy neural networks (FNN), and evolutionary algorithms are additional AI techniques used for diagnosis. AI techniques for induction machine stator fault diagnostics are reviewed and identified by different researchers [33,53]. The figure below is about the general conceptual model for performance analysis. It is based on gas turbine fault diagnostics from a researcher on challenges in aircraft engine gas path health management as showr

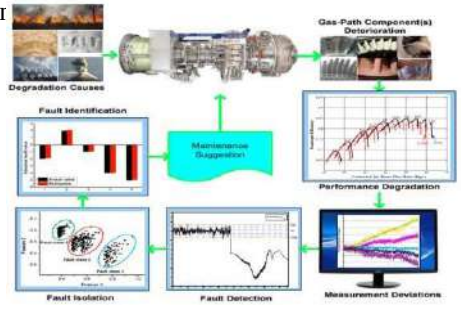


*Figure - 7: Conceptual model of a gas-path fault diagnostics.*

The performance deterioration, measurement deviation, and fault diagnostics are the distinct processes that make up the conceptual model of a gas path fault diagnostics [55] [56]. A lot of AI techniques can reason and show the causal relationship between non-observable health factors and observable measurements. An additional factor is their proficiency in handling huge systems, which may contain several factors and necessitate extensive computations [57].

### c. *Prognosis*

Prognosis is the process of projecting an engine's future state of health based on data gathered based on past and present information. The Remaining Useful Life (RUL), or the amount of safe operating time left before failure, is a practical way to describe a prognosis. Estimating the fault propagation process and being aware of the failure mechanism are prerequisites for RUL estimation [58].

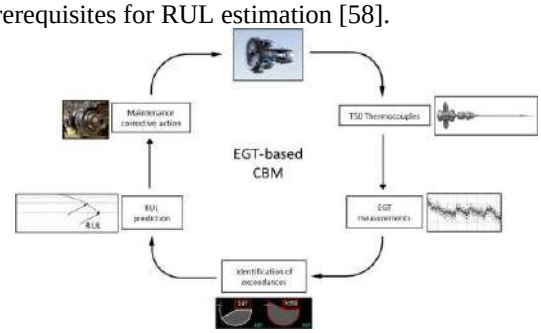


*Figure - 8: EGT-based CBM process with RUL prediction*

Prognosis' primary goal is to provide further warning by projecting or estimating the equipment's failure time. A prognostic is better than a diagnostic from the maintenance point of view since it can stop unanticipated failures, saving further unplanned maintenance expenditures [33,59].

## 2.4 The Economics of CM maintenance

The main objective of CBM is to avoid failures, downtime, and unplanned practices to keep asset's health [60]. Even the lifetime of equipment and the lifespan of its components can be increased with application of CM. For instance, repair rather than replacement of gearboxes can save up to 40% maintenance costs and increase overall performance, according to Renold Gears, a gear box specialist [60] [61].

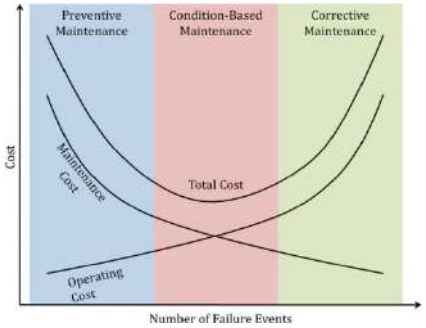


*Figure -9: Cost and benefits comparison of different maintenance approaches*

In aircraft maintenance. From least to most expensive, tasks are chosen according to a hierarchy of difficulty and cost [9]. The primary financial benefits of using CM for MRO and industrial machinery arise by avoiding defects. The prevention of defects results in avoiding production losses brought on by equipment failure. The maintenance costs which can be saved are rather more difficult to quantify, but are likely to relate mainly to the labour costs of breakdown maintenance [62]. If a system's maintainability is not considered from the beginning of its conceptual design until its disposal, its cost cannot be assessed. As a result, a cost model needs for the whole system life cycle [61]. Expenses associated with maintenance operations, output losses or product quality losses are some maintenance expenditures [63].

The cost of failure of the asset corresponds to the loss of profit margin caused by defect [64]. Delay costs are another expense associated with flying an airplane. Delay costs can be significantly decreased with effective and reliable condition monitoring for all systems that cause faults [64]. Unscheduled maintenance is one factor that might affect airline delays. There are different techniques used to calculate the costs and effects of an aircraft delay [65]. Theoretically, CM and extra sensors are used to prevent all other problems, including leaks, fan faults, and valve failures. Implementing CBM in an aircraft environment to replace preventative maintenance would need a lot of testing and verification, particularly for flight critical systems [61].

## III. CBM Application in Aviation

The evaluation of two primary factors such as safety and a strong business case will determine whether or not CBM solutions are taken into consideration. CBM investment approach must be justified by potential maintenance cost savings and greater aircraft availability over present maintenance practices [30]. The general framework of maintenance for commercial aircraft must align with the implementation of CBM. The Maintenance Program Industry Group or MPIG suggested a methodical way to modify the MSG-3 logic. It is performed by introducing an alternative health management process. This program uses acquired data instead of interval-based maintenance tasks [66]. The integration of health management programs for maintenance credit is authorized by Federal Aviation Administration (FAA) [34]. An initially successful CBM application may experience fewer failures over time [30].

### 3.1 Aircraft health management in MRO

MRO business, which is expected with annual turnover of $78.5 billion and accounts for roughly 11% of an airline's cost expenditure, is one of the primary components of the aviation industry. Efficiency gains in aircraft MRO are of great interest because of their influence on airline costs and profitability [67]. Researchers propose a definition of CBM for Adaptative Aircraft Maintenance Planning (ReMAP) project as presented in the Figure below;

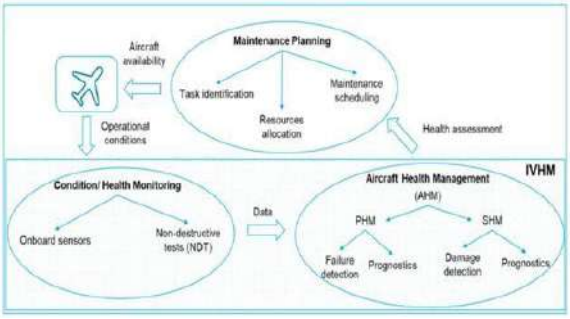


*Figure -10: CBM aviation concept*

Aircraft CM, operational and related event data are used in the process of AHM, also known as integrated aircraft health management (IAHM), to infer the asset's current state of health and forecast its eventual decline over time. In order to detect engine performance degradation and malfunction of engine parts and accessories, Engine Condition Trend Monitoring (ECTM) tracks and measures changes in any of the engine's performance metrics. ECTM is considered to be part of a good engine maintenance program. The main engine monitoring system parameters are oil system, temperatures, vibration**,** pressures, and life usage [68] [69].

### 3.2 Condition Monitoring in MRO

ECM which is the process of engine condition monitoring for key parameters are used to detect impending failures. This assesses engine performance continuous monitoring of various parameters and conditions. Aircraft instrumentation & standard engine is basically used by ECM to facilitate monitoring of different parameters continuously [70]. On-condition monitoring allows for early detection of problems, enabling timely maintenance and preventing costly breakdowns [71]. There was a little increase in the rate of ECM parameter degranation, according to a spread sheet created to compare the parameters at the start and end of the five-month operation [72].

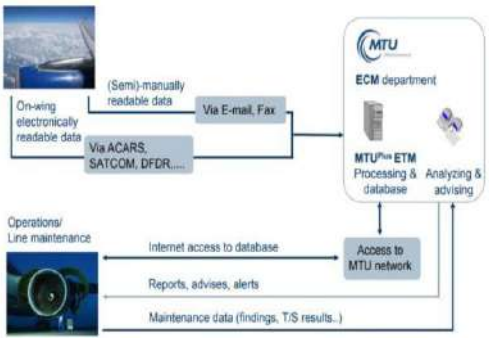


*Figure-11: Engine condition monitoring*

In order to provide efficient maintenance, monitoring the engine condition during operation is a prerequisite. As a result, engine condition monitoring (ECM) is now considered as a standard operating procedure in maintenance [73]. Because of the automatic recording and trend analysis features of modern ECM solutions, the operators have data access.

*Figure -12: Aircraft condition monitoring*

Different mach numbers as a function of EPR are presented together with EGT, FF, N1, and N2 [74]. Aviation ECM and cruise trend analysis techniques have a number of sensor systems, EGT sensing approaches and strategies for the turbine temperature application. Blade temperature control factors are computed using indirect parameters like model-based estimating method for EGT. The characteristics of interest are often inferred from sensor values of physical quantities and an understanding of the physical process, rather than being measured directly [75].

The temperature within gas turbine engines is measured by thermocouples. Similarly there are techniques for measuring higher temperature. Thin film temperature sensors are capable of operating for at least 25 hours in operating settings with temperatures up to 1500 °C [76-77]. Pyrometers are also employed in engine data sensing, where they monitor the radiation that a target emits and establish a temperature correlation between the emittance level and the target. A pyrometer's collection, transmission, detection, data collecting and signal processing modules make up its system components [78].

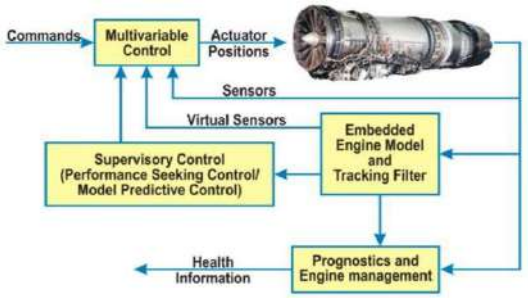


*Figure -13: Model-Based control scheme for modern and future engines*

Tunable diode laser absorptive spectroscopy (TDLAS) is similar to pyrometers which employ absorptive spectroscopy to relate measured intensity to absorbance [79]. Anywhere in the turbine engine, we can obtain extremely accurate instantaneous gas temperature data with the help of an acoustic pyrometer, a non-contact measurement tool [80]. Radioactive isotope technique is used as sensing methods employed in GTE. This technique is employed by several researchers for determining gas temperature in the turbine exhaust area [81].

### 3.3 The concept of CBM in the field of Gas Turbines

A significant obstacle faced by Gas Turbine users is maintaining the engines during the course of their whole lives. The preventive or scheduled maintenance is more advanced maintenance approach which involves maintenance actions after specific time intervals of operation, regardless the condition of the engines [30]. Condition monitoring data are normally collected by using instruments like vibration, pressure, temperature, shafts speed, lube oil, fuel system, exhaust gas analysis, torque and ambient conditions measurements.[82].

Gas turbine diagnostics can specifically address the fuel and lubricant, vibration, gas path, control, and sensor systems [83]. Over the years, the research community has developed a number of techniques for gas turbine diagnostics [33,84]. The most important of these is gas path diagnostics. Model- based and data-driven approaches are the two primary categories into which these techniques can be divided [85]. Research has been done on the impact of malfunctions in a multistage axial compressor's variable stator vanes system. Data have been acquired with the engine data logging system and the locations at which measurements were performed are shown in Figure 7 [86].

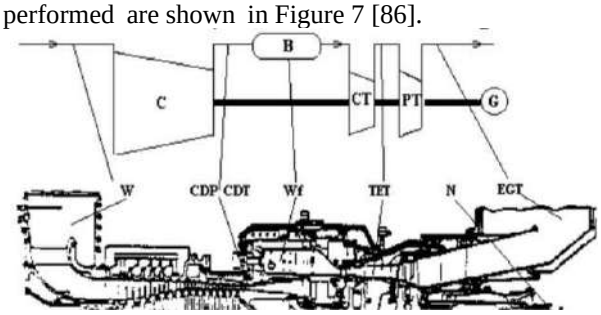


*Figure -14: Engine layout and the measured quantities*

High bypass ratio turbofan engine of a commercial short-range aircraft are equipped with a set of measurements that can be used for CM. Measurements for the number of engine cycles, Active Clearance Control (ACC) valve position and Stator Vane Actuator (SVA) position are also available. The available measurements cover almost a year of operation, corresponding to 1100 cycles [87]. The engine stations and the available measurement set are

depicted in Figure below.

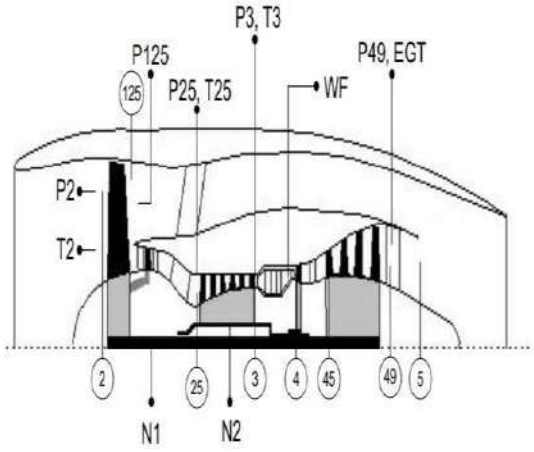


*Figure -15: On-wing available measurements*

Few years ago, a large number of academics have heavily relied on data-driven methodologies for gas turbine diagnostics. They can be categorized into two categories: statistical approaches and artificial intelligence (AI) [33].

## IV. CBM Maintenance Tools and NDT Methods

Through preventative maintenance of aircraft systems and structures that are critical or not critical to safe and economical operations, aviation maintenance guarantees the airworthiness of the fleet of aircraft. Researchers provide an alternative technique to perform CBM maintenance which is based on the real time health status of the aircraft [88]. CBM has capabilities derived primarily from real-time assessment collected from embedded sensors using portable equipment. CBM involves data processing, analysis and correlation to determine maintenance action by collecting massive amounts of data [89].

### 4.1 Different NDT methods and techniques employed in Aerospace

Nowadays there are numerous NDT techniques used in aviation. NDT is divided into various methods of nondestructive testing which is based on a particular scientific principle. The commonly used NDTs nowadays are tabulated below and in each group there are methods which widely used in CBM analysis;

Table 1: Types of NDTs

| GROUP I |
|---|
| Ellipsometry, Endoscope inspection, Vibration analysis Guided wave testing, Hardness testing, Impulse excitation, technique , Surface temper etch, Terahertz evaluation, Machine vision , Weight and Corroscan load, testing , and Visual inspection. |
| Absolute pressure leak testing, Hydrostatic test, Hydrogen leak testing,Tracer-gas leak testing, Mass spectrometer leak testing, Bubble testing and Halogen diode leak testing |

| GROUP II |
|---|
| Acoustic emission testing (AE), Acoustic microscopy, Blue etch anodize (BEA) and Dye penetrant inspection (PT or LPI) |
| Alternating current field measurement, Alternating current potential drop measurement, Barkhausen testing & Direct current potential drop measurement, Magnetic flux leakage testing (MFL), Eddy-current testing (ECT), Magnetic-particle inspection and Remote field testing (RFT) |
| **Radiographic testing (RT)** |
| X-ray computed tomography (CT), Digital radiography (real-time), Neutron imaging, and small controlled area radiography |
| **Ultrasonic testing (UT)** |
| Acoustic resonance technology (ART), Angle beam testing, Laser ultrasonics (LUT), and Electromagnetic acoustic transducer, Internal rotary inspection system (IRIS) , Phased array ultrasonics (PAUT), Time-of-flight ultrasonic determination of 3D elastic constants and Time of flight diffraction ultrasonics (TOFD) |

| GROUP III |
|---|
| Magnetic resonance imaging (MRI), Optical microscopy, Metallographic replicas, Scanning electron microscopy, Resonant acoustic method and 3D computed tomography |
| **Infrared and thermal testing (IR)** |
| Thermographic inspection and Scanning thermal microscopy |
| **Positive material identification (PMI)** |
| **Laser testing** |
| Holographic interferometry, Electronic speckle pattern interferometry, Self-mixing laser interferometry, Low coherence interferometry, Optical coherence tomography (OCT), Profilometry and Shearography |
| **Spectroscopy** |
| Near-infrared spectroscopy, NMR spectroscopy, Raman Spectroscopy, Mid-infrared spectroscopy (MIR),Terahertz spectroscopy and Far-infrared spectroscopy |

### 4.2 Aircraft Inspection

The comprehensive examination and evaluation of an aircraft's systems, parts, and general state constitute an aircraft inspection. Inspections are carried out at several phases, including as major overhauls, routine maintenance, and pre-flight inspections [90]. The test pyramid for all mechanical structural tests (static and fatigue) takes into account material tests at the coupon level, various degrees of structural and component testing of entire aircraft structures (major tests) showed in the Figure 9 [91],

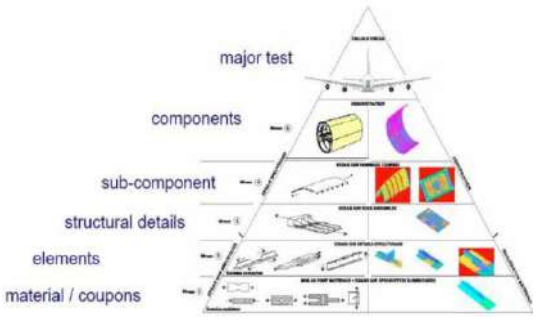


*Figure -16: Test or inspection pyramid*

The length of time between subsequent inspections depends on the aircraft type being used and operations being carried out. An aircraft may undergo an inspection in certain cases following the accrual of a predetermined number of flight hours [91-92]. Aerial aircraft inspections comprise several components, including pre-flight, routine maintenance, yearly, 100-hour, special, NDT, and post-maintenance inspections. The components of inspection services comprise the fuselage, skins, stringers, ribs, pressure bulkhead, wing spar, landing gear, control surfaces like aileron, flaps, stabilizers & slats. They all can have doors disbond, delamination, surface & subsurface cracks, corrosion, 2nd layer crack. Different gas turbine inspection methods, such as remote visual inspection, phased array ultrasound, eddy current array, X-ray fluorescence (XRF), industrial microscopy, 3D laser microscopy, and others, are employed for the areas specified by the manufacturer.

### 4.3 Common types of NDT Inspection

Visual inspections of aircraft are part of MRO activities that combine a number of observational procedures done with the unaided eye [93]. Borescopes, fiberscopes, magnifying glasses, and mirrors are common tools used in visual inspection for engine internal parts. For aviation inspections, the borescope inspection cameras should be bright, high-resolution displays. The flexible probes should also be able to fully move and articulate within the inspection zone. Ultrasonic testing employs high frequency pulses that are above the range of human hearing. Inspecting the material for faults and other defects on the display to evaluates its geometric qualities [94]. In aviation maintenance, ultrasonic inspection is a potent and efficient NDT method.

*Figure -17: Landing gear (L) and turbine blade (R) ultrasonic testing*

Surface temperatures are measured or mapped using thermal nondestructive testing (NDT) techniques when heat moves through an object. The primary benefit of thermography over traditional NDT methods is its ability to quickly and safely check broad areas without requiring access to both sides of the component. However, due to its sensitivity to 3D heat dispersion, infrared thermography is only able to identify somewhat minor flaws [95].

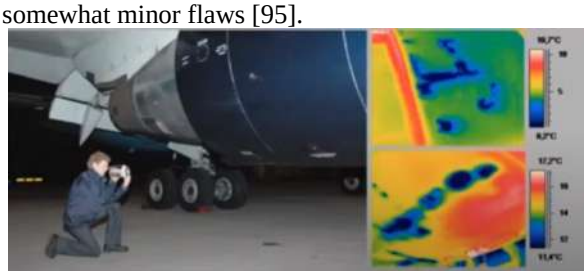

*Figure -18: Thermography inspections on aircraft body and detected spots*

For many years, infrared thermography has been utilized for NDT of aerospace components [96]. Although other representations, such as maxigrams, timegrams, diffusivity maps, and thermograms are the most common way that represent optical stimulation data [97]. Using infrared (IR) cameras, this technology increases inspection speed and simplify the visualization of flaw detection in complicated geometrical parts [98]. Below is an experimental configuration utilized for infrared imaging of the slot and induction thermography of the engine disc [99];

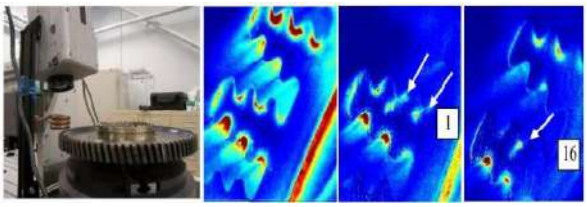

*Figure - 19. Experimental setup used for induction thermography and the infrared images*

Shearography and Holography systems use the difference between two shifted, or "sheared," images to image and measure changes in the surface profile of test objects down to 1 nanometer. This method can also discover extra structural information such as stringers, bulkheads, splices, ribs and overlaps [100]. Laser shearography the main techniques used for NDE of composite structures is nowadays.

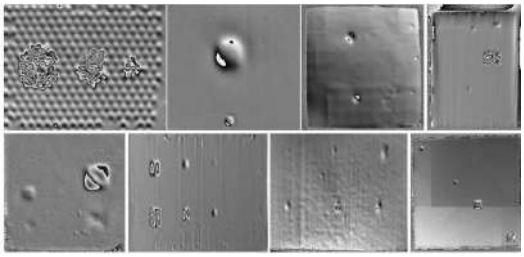

*Figure - 20: Laser shearography phase map from aerospace NDT*

During R&D and production, aerospace turbine components are qualified using digital radiography supported by computerized imaging [101]. Defects such as inclusions, porosity, shrinkage, cracking, core shift, and core break can all be found.

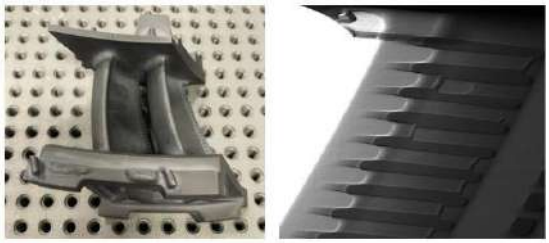

*Figure - 21: Turbine blades and vanes*

## V. CONCLUSION

The CBM approach will be one of the important tools for maintenance in industries. Although it is introduced a few decades ago, CBM approach has been developed in aviation MRO industries from latest digital NDT techniques. Innovations in emerging ICTs and computer innovation in capturing, displaying, editing and interpretation of defect images or videos are being employed in aviation MROs to solve hidden anomalies in different components. As a result this research paper has reviewed the different CBM approaches from different technologies. AI techniques such as ANN, ES, FNN and EA are promising for defect diagnosis in MRO. Furthermore techniques for implementing the CBM approach have been addressed. The visual inspection also shows drastic development in borescope with inspection cameras bright, high-resolution displays and probes with well developed videoscope technologies. Currently digitalized eddy current is in use for different applications. The instrument should be well digitalized for multi-frequency channels and the sorting of channel modules along with other functions. When the digital radiography, shearography, holography and thermography techniques are supported with latest softwares and computerized imaging, will have great benefits in aviations structures as well as gas turbine engines.

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